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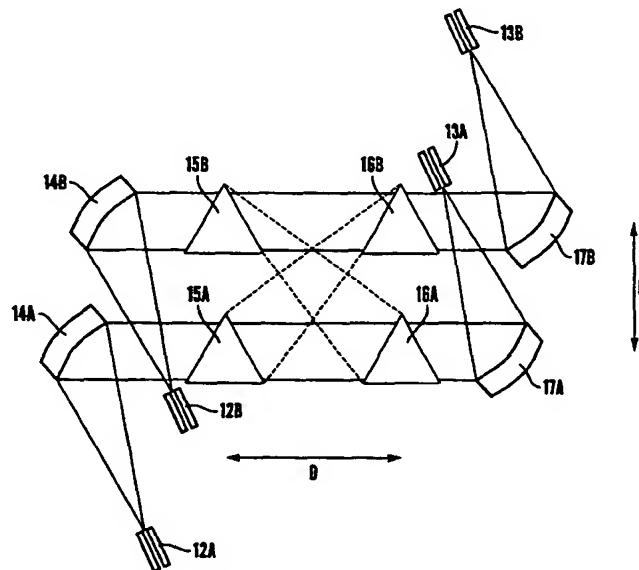
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*For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.*

(54) Title: **INTEGRATED OPTICAL DEVICE**



(57) Abstract: An integrated optical device for selectively directing light from one or more input waveguides (2; 12A) to one or more output waveguides (3; 13A), the device comprising: a slab waveguide (4); one or more input waveguides (2; 12A) directing light into the slab waveguide (4); one or more output waveguides (3; 13A) receiving light from the input waveguide(s) after it has travelled through the slab waveguide (4); and one or more refracting portions (14A; 15A, 16A) the refractive index of which can be altered to refract the light as it passes therethrough, whereby transmission of light between the input and output waveguide(s) can be selectively controlled. A 1xn switch and an nxn switch is described. Such a refracting portion may be used to steer a light beam. It may also be shaped to function in the manner of an optical component, e.g. a prism or lens.



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## INTEGRATED OPTICAL DEVICE

### TECHNICAL FIELD

This invention relates to an integrated optical device for refracting a beam of light. It also relates to an integrated optical device functioning as an optical switch.

### BACKGROUND ART

Various types of integrated optical switch are known. Most of these make use of interference effects to provide selective communication between one or more light inputs and one or more light outputs.

The present invention provides an alternative form of device.

### DISCLOSURE OF INVENTION

According to a first aspect of the invention there is provided an integrated optical device for selectively directing light from one or more input waveguides to one or more output waveguides, the device comprising: a slab waveguide; one or more input waveguides for directing light into the slab waveguide; one or more output waveguides for receiving light from the input waveguide(s) after it has travelled through the slab waveguide; and adjustment means for adjusting the refractive index of one or more refracting portions of the slab waveguide through which the light travels so as to refract the light as it passes therethrough, whereby transmission of light between the input and output waveguide(s) can be selectively controlled.

The present invention also provides a novel integrated optical device for refracting a light beam.

Thus, according to a second aspect of the invention, there is provided an integrated optical device for refracting a beam of light so as to alter its direction of travel, the device comprising a slab waveguide through which the beam is directed and adjustment means for adjusting the refractive index of a portion of the slab such that the direction of light emerging from said portion can be altered by adjusting the refractive index of said portion.

An embodiment of a device according to the second aspect of the invention may be used in the first aspect of the invention.

Preferred and optical features of both aspects of the invention will be apparent from the following description and from the subsidiary claims of the specification.

### BRIEF DESCRIPTION OF DRAWINGS

The invention will now be further described, merely by way of example, with reference to the accompanying drawings

Figure 1 shows a schematic diagram of an embodiment of the first aspect of the invention;

Figures 2 and 3 are sectional views through a ridge waveguide and a slab waveguide formed on a silicon-on-insulator chip;

Figure 4 shows a portion of Figure 1 in more detail;

Figure 5 shows a schematic diagram of another embodiment of the invention;

Figure 6 shows a schematic diagram of a variant of the embodiment shown in Figure 5; and

Figure 7 shows a more detailed view of a preferred form of refracting portion used in the above devices.

### BEST MODE OF CARRYING OUT THE INVENTION

Figure 1 shows an optical chip 1 having an input waveguide 2, a plurality of output waveguides 3 and a slab waveguide region 4 between the input and output waveguides 2, 3. Figure 1 also shows a first parabolic mirror 5, a second parabolic mirror 6 and a triangular refracting portion 4A of the slab waveguide 4.

Light from the input waveguide 2 is confined in a vertical direction, i.e. the direction perpendicular to the plane of the chip 1, but diverges as it travels across the slab

waveguide 4 until it reaches the first mirror 5 which is arranged to collimate the beam and direct it through the refracting portion 4A to the second mirror 6. The second mirror 6 receives a collimated beam from the refracting portion 4A and focuses this towards one of the output waveguides 3.

If the refracting portion 4A has the same refractive index as the slab region 4 on the input and output sides thereof, the beam will pass through the portion 4A without deviation. However, if the refractive index of the refracting portion 4A is altered so as to differ from that of the slab regions 4 on the input and output sides thereof, it will act in the manner of a prism and refract the beam of light as it passes therethrough.

The refracted beam of light remains collimated but strikes the second mirror 6 at a different angle and so is focussed thereby at a different position. Thus, by appropriate adjustment of the refractive index of the refracting portion 4A, it can be arranged so that the light is directed towards a selected one of the output waveguides 3, depending upon the difference in refractive index of the said portion 4A and the slab region 4.

In a preferred arrangement, the refracting portion 4A may be part of the slab region 4 on top of which is provided a heater, e.g. in the form of a series of resistance heaters formed by narrow lines 7 of conductive material, deposited on the upper surface of the slab region as shown in Figure 4.

By arranging the heaters 7 in a triangular pattern, they can be used to change the temperature, and hence the refractive index, of a triangular portion of the slab waveguide 4 beneath the array of heaters 7. Electrical connections to the heaters 7 are not shown in Figure 4.

The application of appropriate heating currents to the heaters 7 thus controls the refractive index of the triangular portion 4a of the slab waveguide 4 and thus which of the output waveguides 3 the light is directed to. The device thus functions as an optical switch.

The chip 1 preferably comprises silicon and is preferably a silicon-on-insulator chip.

The input waveguide is preferably a rib waveguide 8 formed in a silicon layer 9 in a known manner. Figure 2 shows a cross section through a rib waveguide formed in a silicon layer 9 supported on a substrate 10 (typically also silicon) with an insulting layer 11 (typically silicon dioxide) therebetween. The height of the rib (from the top surface thereof to the oxide layer 11) is typically around 8 microns (but may be other sizes) and the thickness or height of the silicon layer on either side of the rib is typically around 5 microns. Other types of waveguide, including optical fibres, may also be used for directing light into the slab region 4.

Figure 3 shows a cross-section through the slab waveguide region. This preferably comprises a continuation of the silicon layer 9 in which the rib waveguides are formed and thus also has a height of around 8 microns.

The slab region 4 preferably confines the light in a vertical direction, i.e. a direction perpendicular to the plane of the slab region, but does not confine the light in a horizontal direction so the light spreads out within the slab region 4 after leaving the input waveguide 1.

The parabolic mirrors 5, 6 may be formed by etching a recess in the silicon layer 9 so as to form a vertical curved wall on one side of the recess which forms a reflective surface. Preferably, reflection at this surface occurs by total internal reflection. In the case of silicon, this can be achieved by arranging so that the angle of incidence on the parabolic mirror is greater than 16 degrees, which is the critical angle. This holds for both polarisations so polarisation dependent losses (PDL) are low.

Other forms of reflective devices may be used and the term mirror as used herein is intended to include such devices.

Figure 4 shows the triangular array of heaters 7 in more detail. The array preferably comprises a series of resistance heaters, e.g. comprising a narrow strip of aluminium or tungsten, e.g. a titanium, tungsten, gold alloy, and may be between 5 and 20 microns wide and 0.5 to 2.0 microns thick with a spacing between adjacent strips (centre to centre) of about 30 to 50 microns. An example comprising strips of tungsten alloy around 1 micron thick, 10 microns wide and at 40 micron intervals gave

satisfactory results. The lines are preferably perpendicular to the axis of the light beam but may be parallel thereto.

The array of heaters may be arranged in a variety of patterns and the lines can be individually controlled to provide the required temperature change and/or temperature gradients across the device. Changes in temperature of several tens of degrees Centigrade, e.g. in the range of 10-100 degrees Centigrade, produce a change in refractive index of the silicon layer of less than one percent but this is sufficient to cause the required deviation of the beam. Greater changes in refractive index cause a greater deviation and will be required if the switch is provided with a greater number of output waveguides. The example shown comprises four output waveguides 3 but many more may be used, e.g. a hundred or even several hundred.

The distance between the second mirror 6 and the output waveguides 3 may be increased to provide greater separation between the output waveguides for a given angle of deviation caused by the refracting portion 4A, although the shape of the mirror 6 needs to be altered as well so that the light is still focussed on the input ends of the output waveguides.

In a typical arrangement, such as that shown in Figure 1, the collimated beam may have a width of around 100 microns and the triangular region 6A has similar dimensions so as to interrupt the entire width of the beam. The components of the device would be spaced apart by distances greater than indicated in the schematic diagram and the overall dimensions of the chip may typically be around 15 mm long (from the input side to the output side) and around 5 mm wide. Other layouts and dimensions may, however, be used depending on the circumstances.

Whilst the above description relates to an integrated optical switch with a triangular portion of a slab waveguide located so as to function in the manner of a prism, other arrangements may be used. Other means may be used to actively control the refractive index of a portion of the slab waveguides, for example charge carrier injection, or depletion. The region of the slab waveguide the refractive index of which is changed may also be of other shapes. Whilst a triangular shape has the advantage of simplicity and the use of a simple triangular shape in conjunction with a collimated

beam avoids introducing optical aberrations, other shapes, e.g. with convex and/or concave sides, may be used, e.g. to function in the manner of a lens.

Such a device may be used in other applications which require beam steering, i.e. refraction of a beam of light so as to alter its direction of travel. A simple beam steering device may comprise a slab waveguide through which a light beam is directed with adjustment means for adjusting the refractive index of a portion of the slab region so the direction of light emerging from the portion can be altered by adjusting the refractive index of that portion. As described above, the portion preferably has a shape selected to imitate an optical component such as a prism or a lens.

The ends of the input and output waveguides are preferably provided with tapers to widen the ends thereof to provide a better match to the planar waveguide. Typically, the ends have a width of around 12 microns. This provides a restriction on the spacing of the output waveguides and the typical centre to centre spacing therebetween may be double this figure, i.e. about 24 microns. With a parabolic mirror having a focal length of about 6000 microns, the angular deviation between adjacent waveguides is the inverse tan of  $24/6000$ , i.e. about 0.28 degrees. With silicon, a temperature deviation of 200 degrees Centigrade gives a refractive index shift of about 0.04. Thus, with a prism having an apex angle of 150 degrees, the maximum deviation is about 10 degrees, so providing the capability to switch between up to 35 output waveguides.

Prisms could be cascaded to provide more deviation and hence a higher number of switching outputs.

Figure 1 shows a  $1 \times n$  switch, in which light from a single input waveguide 2 can be switched to any one of a plurality  $n$  output waveguides 3. Figure 5 shows an  $n \times n$  switch in which light from any one of  $n$  input waveguides 12A, 12B, ... can be switched to any one of  $n$  output waveguides 13A, 13B, ... (whilst Figure 5 only shows two input and two output waveguides, the arrangement can be extended to a larger number, e.g. up to one hundred or more).

Input waveguide 12A is positioned at the focus of an input parabolic mirror 14A associated therewith and, as shown in Figure 5, light from input waveguide 12A is collimated by the input mirror 14A and directed towards a first refracting portion 15A. If the refractive index of refracting portion 15A is the same as the surrounding slab material 16, light passes through the first refractive portion 15A to a second refracting portion 16A. If the refractive index of the second refracting portion 16A is the same as that of the surrounding slab material, light passes through the second refracting portion 16A to an output parabolic mirror 17A which focuses the light to output waveguide 13A which is positioned at the focus of the mirror 17A.

Alternatively, light from the first input waveguide 12A may be switched to the second output waveguide 13B by altering the refractive index of the first refracting portion 15A so as to refract the light to a refracting portion 16B associated with the second output waveguide 13B. The refracting portion 16B is controlled to refract the light to a parabolic mirror 17B which focusses the light into the second output waveguide 13B. Thus, light from the first input waveguide can be directed via components 14A, 15A, 16A and 17A to the first output waveguide 13A, or via components 14A, 15A, 16B and 17B to the second output waveguide 13B.

The system can be extended by providing N input waveguides 12A – 12N, N input parabolic mirrors 14A – 14N, N first refracting portions 15A – 15N, N second refracting portions 16A – 16N, N output parabolic mirrors 17A – 17N and N output waveguides 13A – 13N. Light can thus be directed from the first input waveguide 12A to the nth output waveguide by components 14A, 15A, 16n and 17n.

Similarly, light may be directed from any of the input waveguides 14A – 14N to any of the output waveguides 13A – 13N. Figure 5, for instance, shows light being directed from input waveguide 12B via components 14B, 15B, 16B and 17B to second output waveguide 13B and (via the dotted lines) from input waveguide 12B via components 14B, 15B, 16A and 17A to first output waveguide 13A.

It should be noted that Figure 5 is highly schematic in that, in practice, the spacings between components and the angles of refraction will be very different from that shown. In particular, the spacing D between the first refracting portions 15A, 15B,...



and the corresponding second refracting portions 16A, 16B, ... will be considerably greater than that shown, e.g. of the order of 100,000 microns (10cm). This enables the nxn arrangement shown in Figure 5 to switch between a greater number of waveguides than the 1xn arrangement shown in Figure 1, as an increase in the spacing D enables the separation between signals for a given angle of deflection by the refracting portions to be increased without affecting the arrangement of the components at each end of this path. This avoids any problems which might arise due, for instance, to the output waveguides having only a small acceptance angle.

With the nxn arrangement shown in Figures 5 and 6, the refracting portions in each set are typically spaced apart by a distance E of about 200 microns. Thus, with a prism capable of providing a maximum deviation of about 8 degrees, as described above and a spacing D of 1 cm this allows switching between up to 7 outputs. However, this arrangement can be enlarged further without changing the geometry of the input and output optical paths. Again, cascading of prisms may be used for higher way switching.

It will be appreciated that in the arrangement shown in Figure 5, each input beam has a mirror and first refracting portion associated therewith, each of the input and output waveguides are positioned at the focus of the associated parabolic mirror and the individual members of each set of components are all orientated in approximately the same direction.

Figure 6 shows an alternative embodiment which is similar to that shown in Figure 5 but in which a single large input parabolic mirror 18 replaces the individual mirrors 14A, 14B, ... and a single, large output parabolic mirror 19 replaces the individual mirrors 17A, 17B, ... In this case, the input waveguides 20A, 20B, ... are angled with respect to each other as are the output waveguides 21A, 21B, ...

In all the embodiments described above, other forms of reflective device having the property that the angle of reflection depends on the angle of incidence rather than the point of incidence of the light on the device may be used in place of the parabolic mirrors.

Figures 1 to 6 illustrate each refracting portion as a single triangular prism. As described above, the refractive index of the prism is changed by heating the prism by means of heating elements. As it is not usually possible to cool the prism to reverse the direction of refraction, a preferred arrangement is for each prism to comprise two opposing triangles side by side as shown in Figure 7. The first prism 22 deflects the beam in one direction and the second prism 23 deflects it in the opposite direction so the appropriate prism is activated depending on the directions of refraction required. The range of refraction angles is thus doubled.

In order to reduce the power consumption of the refracting portions, the device is preferably formed on a suspended portion of a chip, e.g. by removing the silicon beneath the device. The silicon may be removed from beneath the whole device or just from a triangular area immediately below the heated portion so the shape of the heated portion is defined by a shape etched in the silicon layer as well as by the layout of the heating elements.

Claims

1. An integrated optical device for selectively directing light from one or more input waveguides to one or more output waveguides, the device comprising: a slab waveguide; one or more input waveguides for directing light into the slab waveguide; one or more output waveguides for receiving light from the input waveguide(s) after it has travelled through the slab waveguide; and adjustment means for adjusting the refractive index of one or more refracting portions of the slab waveguide through which the light travels so as to refract the light as it passes therethrough, whereby transmission of light between the input and output waveguide(s) can be selectively controlled.
2. An integrated optical device for refracting a beam of light so as to alter its direction of travel, the device comprising a slab waveguide through which the beam is directed and adjustment means for adjusting the refractive index of a refracting portion of the slab such that the direction of light emerging from the refracting portion can be altered by adjusting the refractive index of said portion.
3. An integrated optical device as claimed in claim 1 with a single input waveguide and a plurality of output waveguides, the adjusting means comprising a refracting portion the refractive index of which is controlled to determine which of the output waveguides the light is directed to.
4. An integrated optical device as claimed in claim 1 in which the adjusting means comprises: a first refracting portion of the slab waveguide associated with each input waveguide and a second refracting portion of the slab waveguide associated with each output waveguide, whereby transmission of light between the input and output waveguide(s) can be selectively controlled so that light from a selected input waveguide is refracted by the first refracting portion associated therewith to a selected second refracting portion which then refracts the light to the output waveguide associated therewith.

5. An integrated optical device as claimed in claim 4 comprising a plurality of input waveguides and a plurality of output waveguides
6. An integrated optical device as claimed in any preceding claim in which the adjustment means comprises heating means for heating the or each refracting portion of the slab to thereby alter its refractive index.
7. An integrated optical device as claimed in claim 6 in which the heating means comprises a plurality of resistance heaters provided over the or each refracting portion.
8. An integrated optical device as claimed in claim 7 in which the resistance heaters comprise strips of aluminium, tungsten or alloys thereof.
9. An integrated optical device as claimed in any preceding claim in which the or each refracting portion has a shape selected to function in the manner of an optical component.
10. An integrated optical device as claimed in claim 9 in which the shape is substantially triangular whereby the said refracting portion acts in the manner of a prism.
11. An integrated optical device as claimed in any preceding claim comprising one or more mirrors for directing light through and/or receiving light from the or each refracting portion.
12. An integrated optical device as claimed in claim 11 in which a parabolic mirror is used to direct a collimated beam of light through the or each refracting portion associated with an input waveguide.
13. An integrated optical device as claimed in claim 12 in which a parabolic mirror is used to receive a collimated beam of light from the or each refracting portion associated with an output waveguide to focus the beam of light towards the selected output waveguide.

14. An integrated optical device as claimed in any preceding claim in which the slab region comprises a silicon layer which confines the light therein in a direction perpendicular to the plane of the slab but allows light therein to spread out within the plane of the slab.
15. An integrated optical device as claimed in claim 14 formed on a silicon-on-insulator chip.
16. An integrated optical device as claimed in claim 10 or any claim dependent thereon in which the refracting portion comprises two triangular shaped parts which each act in the manner of a prism but are arranged to deflect the light in opposite directions.

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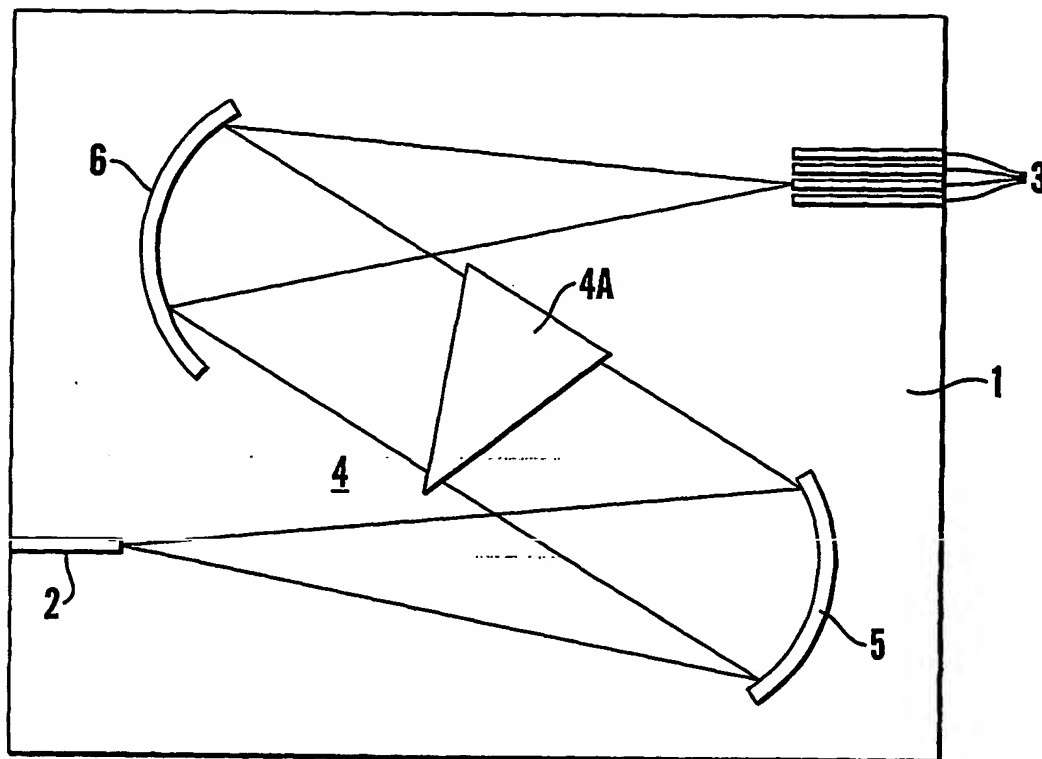


Fig. 1

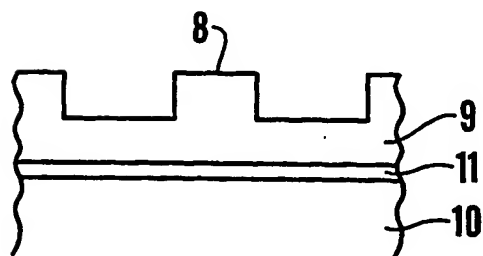


Fig. 2

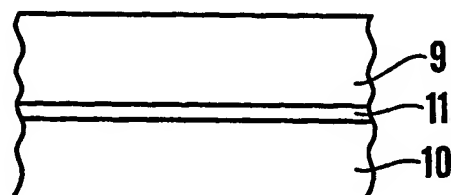


Fig. 3

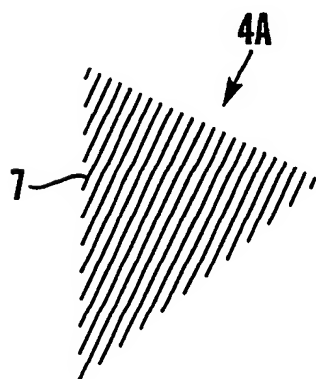


Fig. 4

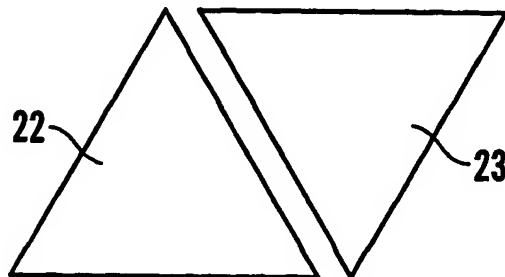


Fig. 7

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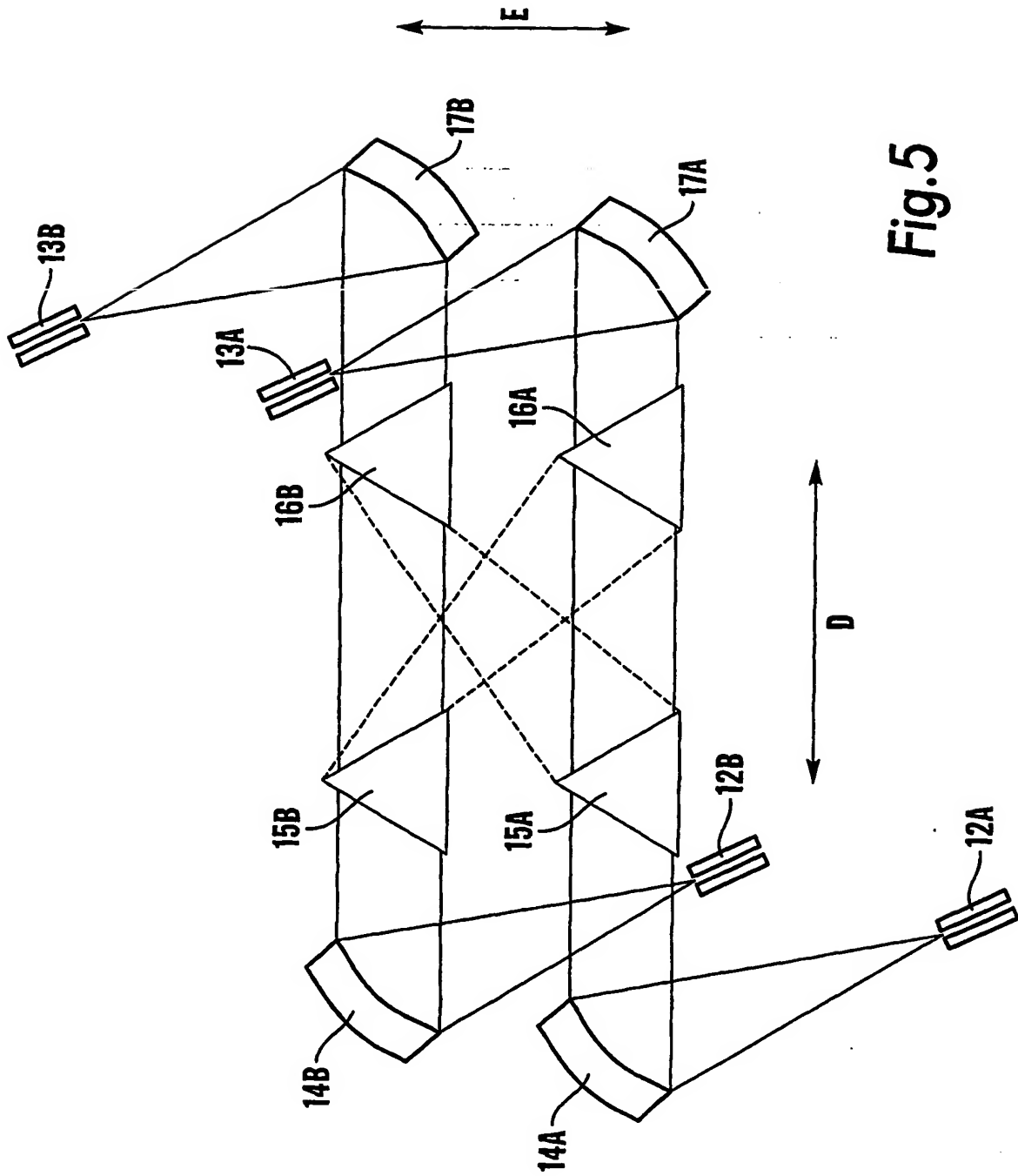


Fig. 5

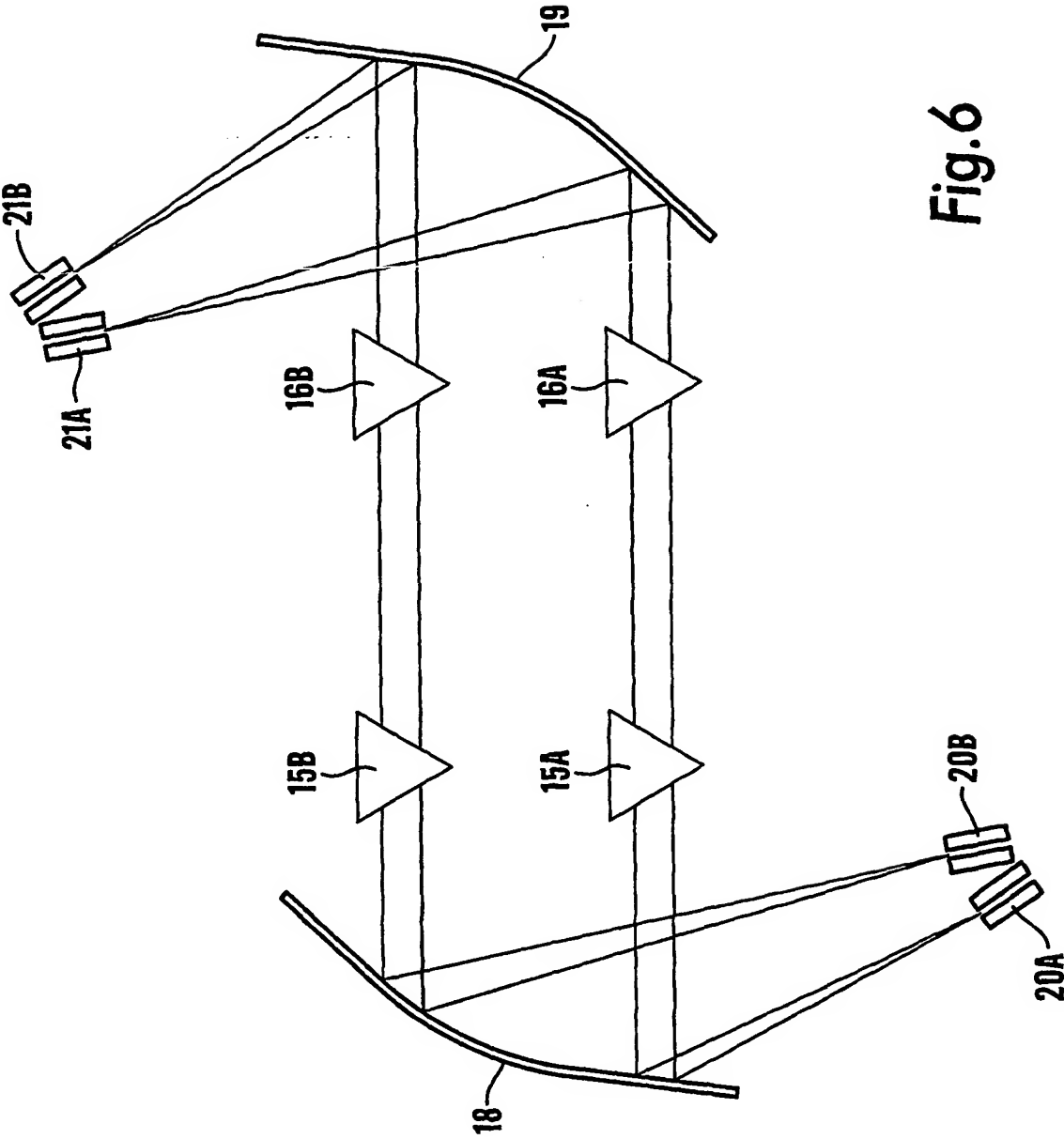


Fig.6



## INTERNATIONAL SEARCH REPORT

PC 1/GB 01/00880

## A. CLASSIFICATION OF SUBJECT MATTER

IPC 7 G02F1/313 G02F1/025 G02B6/34

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 G02F G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, INSPEC

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 623 566 A (LEE HYUNG J ET AL) 22 April 1997 (1997-04-22) column 3, line 41 -column 7, line 66	1-9, 14
X	FR 2 635 198 A (COMMISSARIAT ENERGIE ATOMIQUE) 9 February 1990 (1990-02-09) page 9, line 06 -page 14, line 25; figure 1	1-5, 11-13



Further documents are listed in the continuation of box C.



Patent family members are listed in annex.

## \* Special categories of cited documents:

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Date of the actual completion of the international search

13 June 2001

Date of mailing of the international search report

22/06/2001

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	FISH G A ET AL: "SUPPRESSED MODAL INTERFERENCE SWITCHES WITH INTEGRATED CURVED AMPLIFIERS FOR SCALEABLE PHOTONIC CROSSCONNECTS" IEEE PHOTONICS TECHNOLOGY LETTERS, IEEE INC. NEW YORK, US, vol. 10, no. 2, 1 February 1998 (1998-02-01), pages 230-232, XP000733813 ISSN: 1041-1135	1-5
Y	the whole document	6-10
Y	US 4 762 383 A (YAMASHITA TSUKASA ET AL) 9 August 1988 (1988-08-09) column 3, line 55 -column 6, line 47; figure 7	9,10
A	US 5 317 446 A (MIR JOSE M ET AL) 31 May 1994 (1994-05-31) column 1, line 46 -column 2, line 61	16
X	US 4 143 941 A (SOREF RICHARD A) 13 March 1979 (1979-03-13) column 4, line 42 -column 7, line 16; figure 11	1-3
Y	US 4 753 505 A (WATANABE TARO ET AL) 28 June 1988 (1988-06-28) column 1, line 43 -column 4, line 60; figure 3	6-9
X	KEIL N ET AL: "REARRANGEABLE NONBLOCKING POLYMER WAVEGUIDE THERMO-OPTIC 4X4 SWITCHING MATRIX WITH LOW POWER CONSUMPTION AT 1.55 M" ELECTRONICS LETTERS, IEE STEVENAGE, GB, vol. 31, no. 5, 2 March 1995 (1995-03-02), pages 403-404, XP000498206 ISSN: 0013-5194 the whole document	1-9